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Thermally tunable bandgaps in a hybrid As_2S_3/silica photonic crystal fiber

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ABSTRACT

We report the fabrication and characterization of a hybrid silica photonic crystal fiber (PCF) with integrated chalcogenide glass layers and we show how the bandgaps of the fiber can be thermally tuned. The formation of the high-index chalcogenide films on the inner surface of the PCF holes revealed resonances as strong as ~35 dB both in the visible and infrared regime. Temperature measurements indicate that the transmission windows can be tuned with a sensitivity as high as ~3.5 nm/°C. The proposed fiber has potential for all-fiber filtering and temperature sensing.

Keywords: Chalcogenide glass, hybrid fiber, nonlinear materials, tunable bandgaps, fiber device

1. INTRODUCTION

One of the main advantage of photonic crystal fibers (PCFs) is the ability to control their guiding properties by modifying the geometric characteristics of the cladding holes, such as hole size, pitch, etc[1]. PCFs are usually made from glass[1] or polymer[2] or even a combination of other materials[3]. Silica-based PCFs are mainly used for sensing devices and generation of supercontinuum[4]. On the other hand, polymer planar waveguides or PCFs are used for the development of polymer Bragg grating sensors[5-8] or biosensors[9,10] due to their low Young's modulus and biocompatibility properties, respectively. The ability to infiltrate the cladding holes of the PCF with novel functional nanomaterials created a new class of fibers known as *hybrid PCFs*[11]. Several research groups around the globe are working towards the development of novel tunable fiber devices by combining different advanced optical materials with PCFs, such as polymeric organosilicon compounds[12-14], liquid crystals[15], chalcogenide glasses[16,17], etc. Recently it has been shown that even soft-glasses can be integrated within polymer PCFs[18]. In this paper, we demonstrate the deposition of nanometer-scaled thick As_2S_3 films inside the holes of a silica PCF[16]. The high index films introduce an antiresonant guidance mechanism and we present preliminary results on how the high thermo-optic coefficient of chalcogenide glass films compared to the silica host material, provide the ability to tune the bandwidth of the resonant windows. The thermal sensitivity was found to be as high as ~3.5 nm/˚C from 22˚C up to 70˚C.

2. HYBRID AS_2S_3/SILICA PCF CHARACTERIZATION

2.1 Chalcogenide glass solution and fiber preparation

For our experiments we used commercially available bulk chalcogenide glass with the stoichiometric composition of As_2S_3. The bulk glass was then grinded into powder and dissolved in ethylenediamine (EDA) in concentration of ~50mg/ml. In order to expedite the dissolution process of the glass, the nanocolloidal solution was stirred for 2 days at room temperature. The final solution was then infiltrated inside the holes of a silica PCF by means of capillary forces and placed inside the fume hood at room temperature to allow the solvent to be removed smoothly. The fiber was then further annealed at 100˚C for 12 hours to achieve the maximum solvent evaporation. The final filled length was ~5 cm. The initial silica PCF used in our experiments was an ESM-12 (by NKT Photonics) with hole diameter d = 3.5 um and pitch (distance between the holes) Λ = 7.7 um. The outer diameter of the fiber was 125 um. Figure 1(a) shows a scanning electron micrograph (SEM) image of the hybrid As_2S_3/silica PCF and Fig. 1(b) shows a section of the cladding holes with formed nanoscaled-thick chalcogenide glass layers. In order to further verify the existence of the As-S glass inside the holes of the fiber we used Energy-dispersive X-ray (EDX) spectroscopy.

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Figure 1 (c) shows the EDX spectrum, which confirms the existence of As and S elements in the coated inner surface of the holes of the PCF. The accurate determination of the thickness of the formed chalcogenide glass films was not possible because the thickness of the layers was a few tens of nanometers. One possible way to determine the exact thickness of the films is to use Atomic Force Microscopy (AFM), which has a resolution down to few nanometers.

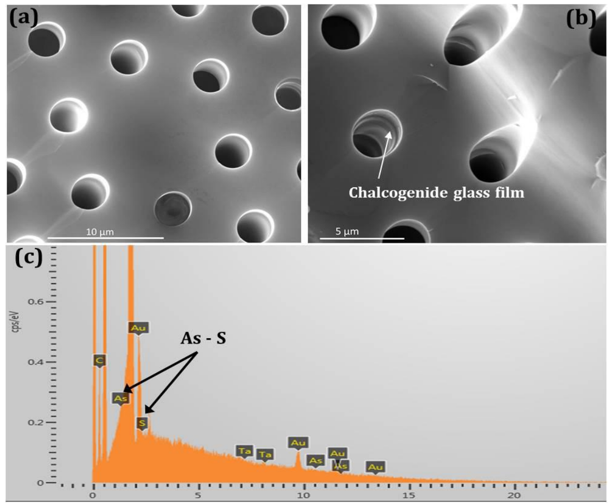

Figure 1. (a) SEM image of the hybrid chalcogenide/silica PCF (b) Angled cleaved end-facet of the fiber showing the cladding holes of the fiber having thin chalcogenide films. (c) EDX spectrum clearly indicating the presence of As and S lines.

2.2 Characterization of the hybrid PCF

The characterization of the hybrid PCFs was made using a supercontinuum source (SuperK Versa, NKT Photonics) with a spectrum from 475 – 2000 nm. The light was coupled in the fiber using a 40x microscope objective and the output beam was expanded using a 100x objective. Any undesired cladding light was blocked using an iris while only the light from the core was collected using a 10x objective and a multimode fiber. All measurements were recorded with an Optical Spectrum Analyzer (OSA) with minimum resolution of 0.1 nm. Figure 2 shows the experimental set-up and the near field profile of the fiber recorded with a high resolution CCD camera indicating the presence of the field in the high index inclusions.

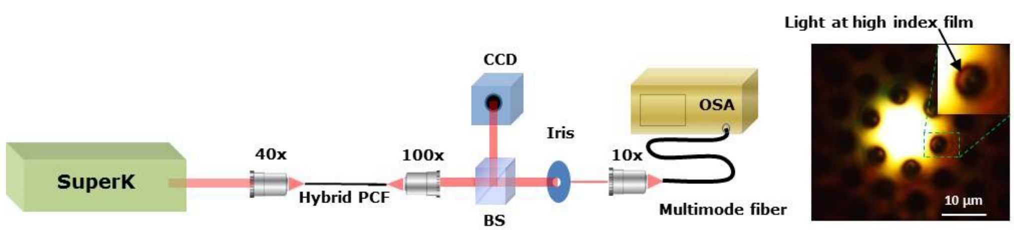

Figure 2. Experimental set-up and the near-field profile of the fundamental guided mode showing that a certain fraction of the light is guided in the high index films.

3. RESULTS AND CONCLUSIONS

Chalcogenide glasses possess, apart their extremely high nonlinearity[19], also other important properties, such as a reversible photostructural effects under illumination close to the bandgap of the material, as well as relatively high thermo-optic coefficient[18,20]. In this work, we investigated the thermo-optic effect of thin chalcogenide glass films formed from an initial nanocolloidal glass solution. The high-index inclusions revealed antiresonant guidance with transmission bands as strong as ~35 dB, as shown in Fig. 3 (a). The position of the resonant windows depends on the refractive index of the high-index films, their thickness and the geometry of the initial PCF. The transmission dips can be predicted using the ARROW model[21]. Figures 3(a) and 3(b) show the transmission spectra of the hybrid fiber for increasing and decreasing the temperature from room up to 70˚C, respectively. It is clear that the red-edge of the transmission windows is blue-shifting when the temperature increases. This is because the refractive index contrast between silica and chalcogenide is decreasing due to the negative thermo-optic coefficient of the high-index chalcogenide films[20]. Similar behavior has also been reported in a polymer fiber filled with chalcogenide[18] and liquid crystals[15,22]. Figure 3 (c) shows how the bandgap edge at 1300 nm shifts over a full cycle of temperature variation indicating the thermal tunability of the bandgaps. The temperature sensitivity was found 3.52 nm/˚C.

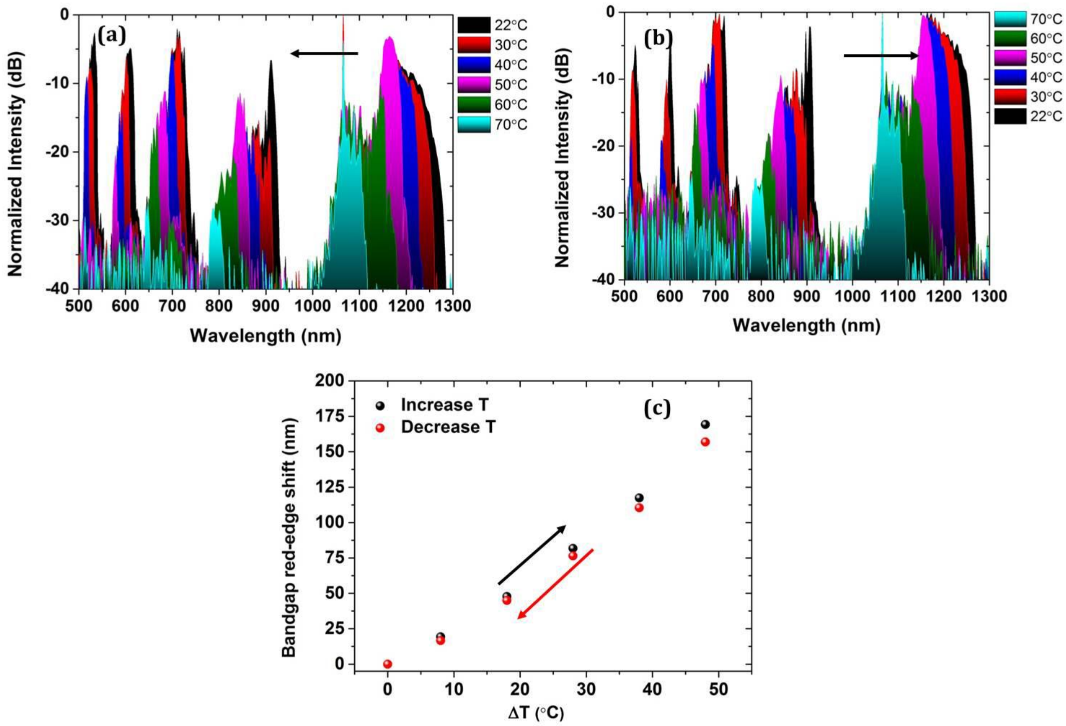

Figure 3. (a) Transmission spectra of the As_2S_3/silica PCF as the temperature increases from 22˚C to 70˚C. (b) Transmission spectra of the same fiber sample as the temperature decreases from 70˚C to 22˚C. (c) Bandgap red-edge shift vs. temperature over a full cycle for the transmission window at 1300 nm.

In conclusion we presented the development of a hybrid As_2S_3/silica PCFs using a cost-effective approach, which allows the possibility of tuning the resonant transmission windows by changing the temperature. The sensitivity was found to be about 3.5 nm/˚C. Liquid crystal filled-PCFs have shown sensitivity up to 6.6 nm/˚C[22]. However it should be emphasized that our proposed technique provides the possibility for further functionalization of the fiber because the air holes are still available to host other materials or analytes. Therefore, the proposed method opens the door to the possibility for the development of all-fiber multi-functional fiber devices for sensing, filtering and nonlinear applications.

4. ACKNOWLEDGMENTS

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